Spatiotemporal characteristics of air circulation in the hollow of Lake Baikal

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The dependence of the initiation and conservation of the in-hollow air circulation inside the boundary layer of the atmosphere over Lake Baikal on synoptic conditions and the time of day has been revealed based on data of airborne measurements in 1991 and 1995 and balloon measurements in 1997–1999. The existence of such a circulation in the presence of the westerly component in the direction of the main flow, beginning from the height of the 850-hPa-isobar surface, is proved. A destructive impact of the fronts on the in-hollow circulation is noticed. The mechanism of vertical distribution of the wind speed and direction in the east branch of the circulation is clarified based on the measurements conducted in Boyarsk village.

Wind regime over Lake Baikal is being formed under the effect of many factors and is characterized by the complexity and strong variability. The relief essentially affects formation of the wind over Baikal. High mountain ridges surrounding the lake have complex shape rugged by a lot of valleys and canyons and favor the appearance of large number of local winds such as Sarma, Bora, and Barguzin. At the same time, they restrict penetration of external air flows into the hollow of the lake. So, well pronounced breeze and mountain-valley circulation are observed near the coast during the whole year.

However, if the aforementioned local winds have been studied quite well, the recently revealed[1,3] phenomenon of the inner hollow circulation (IHC) of air over Lake Baikal needs a more detailed investigation.

Let us briefly remind that this phenomenon is in that there is directed motion of air along the coastal line of the lake: along the west coast it is from north to south (the west branch of the circulation) and along the east coast from south to north (the east branch of the circulation), the velocity of which in different parts of the coast varies from 5 to 10 m/s. This phenomenon was observed in the height range from 400 to 900 m at airborne sounding in 1991 and 1995. The estimate of the height of the circulation cell was obtained in the ground-based expedition in 1997. It is 700 to 1000 m for west and east coasts,[1] and the lower edge of the cell is at the height of 200 to 400 m from the water level.

It should be noted that many scientists investigated the wind regime in the lake hollow. For example, T.V. Shamsheva[5] used a significant bulk of the balloon-borne data obtained at six sites along the lake coast and added to her analysis data from other 7 sites. She constructed a detailed picture of the wind regime over Lake Baikal. Nevertheless, she did not succeed in revealing the IHC. G.A. Gubar[2] approached revealing of the IHC most closely. He presented the approximate diagram of the distribution of flows over the lake and showed that two counter flows are observed in the hollow most often: the "upper flow" blowing along the west coast from north to south and the "kultuk" propagating along the east coast from south to north.

The purpose of this paper is the study of synoptic conditions of the IHC formation, its spatial characteristics, and temporal dynamics. It is based on the data on wind speed and direction obtained in two airborne measurement missions in 1991 and 1995 and two ground-based expeditions in 1998 and 1999, as well as synoptic maps for these periods. The results of the ground-based expedition of 1997 were presented in Ref. 1.

Low-gradient pressure field with unstable wind direction caused synoptic conditions near the ground surface during the expedition in 1991. General transfer of air in the AT_{850} maps has the well pronounced westward component.[3] Pressure fields with low gradients were observed in the region of Lake Baikal in 1995, as in 1991. They were the saddle on June 9 and the central part of anticyclone on June 14. Situation with stable westward wind was observed in the maps of 850 hPa for all days when the flights were carried out.

The velocity of air transport in the IHC was of 5 to 7 m/s in both expeditions with the counterclockwise rotation. The results obtained on June 9, 1995 are interesting. The velocities of air were observed in the ranges 10–17 in the east branch of the circulation and 5–7 m/s in the west branch of the circulation. Such a situation is explained by the presence of high though, the direction of transfer of which coincides with the direction of air motion in the east branch, that leads to an increase in the velocity in the east branch of the circulation. From this it follows, that the pressure formations determining the synoptic situation in this

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region can essentially affect the existence of the circulation and may lead to its destruction.

The expedition of 1998 was carried out since July 20 until August 5. The balloons were launched at two coasts: east one from village Slyudyanka to cape Kabanii, and west one from cape Pokoiniki to cape Malaya Kosa. On the whole, 29 measurements were carried out. When analyzing the situation using the near-ground synoptic maps and maps of 850 and 700 hPa, it was revealed that low-gradient fields were observed in the region of the lake for most time, which caused unstable wind direction and small velocity of transfer in the region under study. Only on July 22 the eastern part of the cyclone determined the weather in the region of measurements. Only one front was observed during the whole period of the balloon-borne sounding. The directions of the principal flow during measurements were calculated taking into account the data of sounding and the absolute topography maps (see two first columns in Table 1).

It is seen from Table 1 that approximately 7% of the total number of possible directions in the AT_{850} map are the directions of the west quadrant, and there are 14% of these directions in the AT_{700} map, while the portions of unstable directions at these surfaces are approximately 79 and 76%, respectively.

Table 1. Repetition (%) of the principal flux direction during balloon sounding campaigns in 1998 and 1999

Transfer direction		1998, 29 launchings		1999, 28 launchings	
		AT_{850}	AT_{700}	AT_{850}	AT_{700}
North		0	3.4	0	7.1
North-east		3.5	0	0	0
East		3.4	0	0	0
South-east		0	3.5	0	0
South		6.9	3.4	0	0
West quadrant	south-west	3.5	3.5	17.8	7.1
	west	0 6.9	3.4 13.8	35.6 85.7	25 92.9
	north-west	3.4	6.9	32.1	60.8
Unstable		79.3	75.9	14.3	0

We did not manage to reveal the IHC in 1998, although it was observed in 1991, 1995, and 1997. The absence of the circulation is explained by the synoptic situation, when stable westward transfer did not affect the lake hollow during a long time. The wind regime at the coast in the lake hollow in this period was completely determined by local winds: mountain-valley circulation and breeze with well pronounced diurnal behavior. Then it follows that the IHC is destroyed in the absence of the mechanism of supporting the circulation, as the westward transfer, which one can assume as such.

The expedition of 1999 was carried out since August 10 until 20. It was carried out at the east coast of the lake in village Boyarsk. Measurements were performed at one stationary site of observation. On the whole, 28 balloons were launched during the expedition. Anticyclonic type of weather was prevalent in this time. One or other part of the anticyclone determined the weather during 4 days of seven, low-gradient high-pressure field determined the weather during the other 2 days, and the cyclone, whose center was in Mongolia, determined the weather in only one first day.

Two fronts connected with this cyclone passed over the site of observation during sounding of the wind. Passing of the second of them led to destruction of the circulation cell. The fronts passing over Boyarsk on August 13 and 17 were observed on the background of the low-gradient pressure field. The south-west part of the cyclone was observed at the height surface of 850 hPa during three days, saddle was during one day, low-gradient field was during two days, and north-west periphery of an anticyclone was observed during one day. Contrast zone was prevalent at the height of about 3000 m, which caused westward of north-west transfer.

Thus, the synoptic conditions during the expedition were characterized by the prevalence of the westward transfer. It is shown in two right-hand columns of Table 1 that most of the observations at AT_{850} and AT_{700} were carried out at the transfer direction in the west quadrant. Twenty launches of 28 have confirmed the existence of the circulation, and 4 of 8 remaining launches were carried out during the passages of the atmospheric fronts at the change of air mass, one launch was carried out under conditions of unstable transfer at the height of 1500 m, and three launches were carried out during the time between 3 and 9 PM of local time (Table 2).

Table 2. Presence (+) and absence (−) of the circulation in the period since August 11 until August 19, 1999

Date	Time of launching the balloon (local)							
	03	06	09	12	15	18	21	24
08.11.99			(+)		(−)			
08.12.99						(±)	(+)	
08.13.99			(−)		(−)		(−)	
08.16.99	(+)			(+)	(±)	(±)	(±)	(+)
08.17.99	(+)		(+)	(+)		(−)	(−)	
08.18.99						(±)		(+)
08.19.99	(+)	(+)	(+)	(+)	(−)	(−)	(±)	(+)

N o t e . (±) means the situation when the lower part of the cell is smoothed.

The confirmation of the existence of circulation obtained in 20 cases is explained by the fact that principal transfer with the westward component was observed during the measurements. It was also noted that weakening and destruction of the circulation occur when the low-gradient field has settled in the region of investigations, for example, on August 13, 1999 at 9 AM (see Table 2). However, the circulation mechanism is inertial. When the low-gradient field has settled on August 17, 1999 at noon, no noticeable weakening of the circulation was observed since previous measurement at 9 AM on August 17, 1999. Other cases, in which the circulation was not observed, will be considered in a more detail below.

One can conclude based on analysis of the effect of the synoptic conditions on the existence and development of IHC, that the presence of westward transfer at the level of the upper boundary of the ridges situated to the west of Baikal is an obligatory condition for the existence of the inner circulation inside the lake hollow. We consider this transfer as the principal mechanism activating the circulation system. It transfers the part of its energy to the west branch of the circulation just after crossing the ridges at the west coast, and affects the east branch before going out of the hollow to the east.

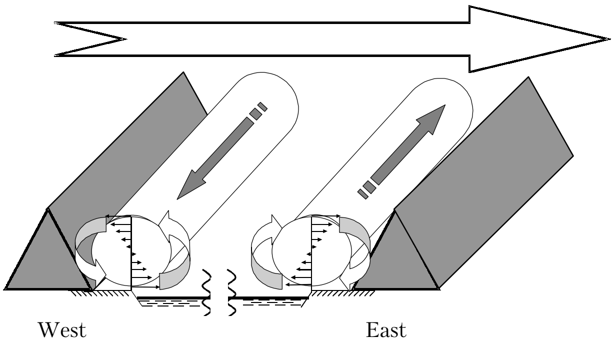

Fig. 1. Diagram of air rotation in the east and west branches of the IHC: ⟹ – principal transfer; ➡ – longitudinal direction of air motion; ↻ – direction of rotation of IHC branches.

Taking into account that IHC is not limited by summer period, but is observed in winter and is a stable phenomenon in time,[1] it is important to emphasize that the circulation cells have a number of peculiarities connected with their physics. It follows from the second Helmholtz theorem which is well satisfied in the atmosphere that the vortex tube can not have a break inside the atmosphere and is closed either to itself or to the ground surface.[4] This is the first variant in our case, namely, the branches of the circulation are closed to themselves, providing for the balance of the momentum. This fact requires that the circulation would not have breaks in the places of its transfer from west branch to the east one and vise versa, that differs it from such phenomena as longitudinal winds. Maintaining the existence of such a complicated and significant formation is only possible at the internal rotation of the branches of circulation, similar to the diagram shown in Fig. 1.

So, investigation of the inner structure of the circulation cell is of interest. It was assumed to perform this job during the expedition in 1998. The method of launching balloons from three sites located on the same straight line perpendicular to the coastal line was used, just near the water line and at two equidistant points on the lake surface and on the land. But the actual synoptic situation did not allow solving the stated problems.

This problem was partially solved in the expedition of 1999. The problem was stated to study the vertical structure of the east circulation cell, its spatial characteristics and temporal dynamics. We have succeeded in obtaining the image of the vertical cross section of the vortex tube (Fig. 2), small arrows show the velocity vectors inside the circulation cell perpendicular to the coast line, and big arrows show the principal transfer.

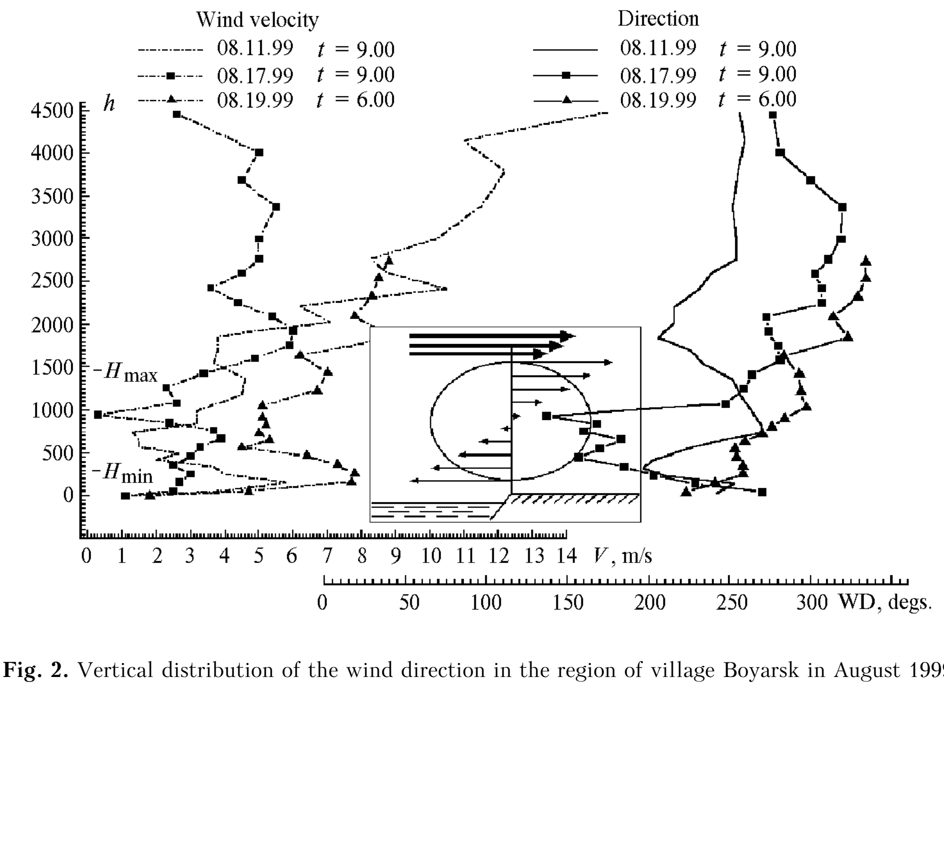

Fig. 2. Vertical distribution of the wind direction in the region of village Boyarsk in August 1999.

For the presentation clarity, the figure also shows some vertical profiles of the wind velocity and direction, which well illustrate the general pattern of the change of wind velocity with height and the behavior of the balloon within the limits of the circulation vortex. The lower boundary H_{min} was at 250–300 m, and the upper boundary H_{max} at 1400 to 1500 m. Such a shape of the curves of wind velocity, where its minimum value is realized at the height of about 800 m, and maxima are near the lower and upper boundaries can be explained by the decrease of the wind velocity component perpendicular to the coastal line in the middle part of the circulation cell. The projection of the balloon trajectory on the ground surface is shown in Fig. 3. It is well seen that, when coming to the area of the circulation cell, the balloon deviates to the left from the direction parallel to the coastal line before reaching the half-height of the vortex, then it deviates to the right and at the outlet from the vortex it takes the direction of the principal transfer. In the central part of the cell we see only the air motion parallel to the coastal line and directed to the north edge of the lake.

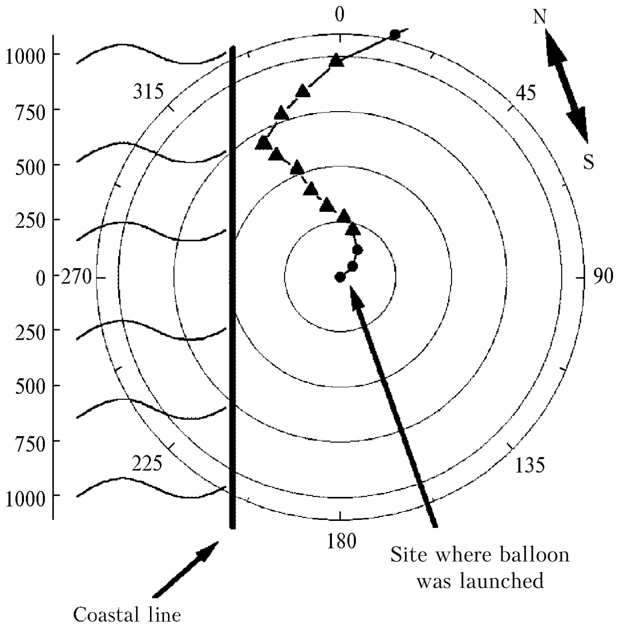

Fig. 3. Horizontal projection of the balloon position in the zone of action of the circulation cell on August 17, 1999, 9 AM of local time : (—●—) – $h < 301$ m and $h \geq 1513$ m – out of the cell, (—▲—) – $301 \text{ m} \leq h < 1513$ m – inside the cell.

One should consider the results connected with weakening and destruction of the IHC separately. Apart from the situation in the region of the lake, when the westward transfer is absent, the circulation can be destroyed under the effect of fronts. The circulation was destroyed in four cases of five fronts passing in the region of village Boyarsk during the period of measurements. Unfortunately, we did not manage to reveal, how quickly the circulation cell is reconstructed after the front passages, because the passage is connected with intensification of cloudiness, and precipitation, that, in turn, prevented launching the balloons. We could renew measurements not earlier than one day after the front passage leading to destruction of the circulation cell.

The data on the behavior of the circulation were obtained in 1999. Weakening or destruction of the vortex tube occurs at 3 PM of the local time in the lower part, from 300 to 600 m over the lake level, and its complete destruction usually occurs at 4 PM. Reconstruction of the vortex tube begins in its upper part from 700 to 1400 m and finishes at about 9 PM (see Table 2). Measurements, in which the circulation is observed in the smooth form or is not observed, were performed from 3 to 9 PM. It is still early to explain this fact, but one can suppose that it occurs due to the upwelling convective fluxes developing in the daytime, which destroy or move the circulation branches over the place of launching a balloon. One can better explain the reason of the destruction of the cell, convection or other mechanisms, only if the data of radio sounding are available, which allow to determine the stability of the temperature stratification of the atmosphere.

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